Finite Element Analysis And Design Of Pressure Vessels For Green Hydrogen Storage

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This research presents a comprehensive design, analysis, and structural evaluation of pressure vessels intended for green hydrogen storage at high pressures ranging from 700 to 800 bar. The design follows the ASME Boiler and Pressure Vessel Code (Section VIII) to ensure safety and compliance with industrial standards. A comparative study is conducted on three geometrical configurations—horizontal cylindrical tanks with dished ends, spherical tanks, and rectangular tanks—assessing their structural performance under extreme pressure and thermal loading. Finite Element Analysis (FEA) is employed to evaluate stress distribution, deformation characteristics, and global structural integrity, utilizing the Von Mises yield criterion to identify critical stress zones. The findings indicate that the spherical aluminium alloy pressure vessel exhibits the lowest deformation (9.81×10^{-8} mm), lowest equivalent stress (6.09×10^{-4} MPa), and lowest equivalent strain (8.58×10^{-9}), ensuring even pressure distribution, reduced risk of structural failure, enhanced cost-effectiveness, and superior durability. This makes it the optimal choice for underground hydrogen storage applications. The study emphasizes the importance of material efficiency and safety in high-pressure hydrogen containment, aiming to develop a reliable and cost-effective storage solution that aligns with sustainable energy goals.

Introduction

Hydrogen is a highly versatile energy carrier with numerous uses across a variety of significant fields including industry, transport, and electricity generation. Its highly impressive high energy density, combined with the benefit that it burns cleanly, makes hydrogen extremely beneficial across a variety of fields of application including transport systems, industrial manufacturing processes, and electrical power generation.

However, efficient storage of hydrogen is extremely difficult, particularly with respect to the high-pressure conditions necessary to achieve in order to realize a practical level of energy density. Globally, there is a wide range of different forms of storage under development with a view to overcoming these issues, including hydrogen gas compressed hydrogen, liquid hydrogen, and hydrogen stored in metal hydrides. Of these, compressed hydrogen storage is the most developed method in practice, mainly due to its efficiency and scalability, and therefore is an option of choice in most applications.

Literature Survey

Organiz This extensive study investigates three different geometries—spherical, cylindrical, and rectangular prisms—each specifically engineered to contain 1 kilogram of hydrogen gas at pressures of 700 to 800 bar. The journal paper carefully incorporates the most recent advancements and developments in the areas of composite materials, pressure vessel design techniques, and advanced computational simulations to evaluate these geometries effectively. Some of the most significant references that form the backbone of this paper are the research by Qiang Cheng et al. (2024)[1] on the use of aluminum alloy tank liners, and the results by Shahrzad Daghighi et al. (2024)[3] on nonconventional pressure vessels, thus laying a robust foundation for this extensive comparative study. In addition, the study proceeds with an extensive discussion regarding the pivotal significance of material selection, choosing Stainless Steel, AluminiumAlloy, and Titanium Alloy to be the ideal choices owing to their enhanced mechanical properties, flawless longevity, and beneficial weight-to-strength ratio. Physical storage methods such as compressed and liquefied hydrogen, alongside material-based approaches like metal hydrides and carbon-containing substances have been discussed [6]. The study identifies salt caverns as the most favorable option for short-term storage, while depleted reservoirs and aquifers offer long-term solutions[7]. The paper highlights the economic and safety benefits of UHS (underground Hydrogen Storage)and explores its potential in the Australian context[8] . Further research into hybrid storage systems and LOHCs (Liquid organic hydrogen carriers) for practical applications are recommended[9]. The paper also covers industrial and underground hydrogen storage developments, including global initiatives and challenges[10]. The thickness of shell has been computed based on ASME standards [11,12].

Besides, the introduction explains the significance of structural integrity, which involves ensuring that the construction is stable and dependable in the long term. It also explains the significance of reducing deformation, or change in shape, while optimizing material usage in a way that is resource-saving and reduces waste, while upholding required safety standards that protect people and the environment. This study meticulously aims at a comparative study of the performance characteristics of the three geometries in question. It examines such aspects as their modes of deformation, the way stress is distributed across the structures, and evaluates their cost-effectiveness by using Finite Element Analysis (FEA) techniques in the ANSYS software environment, fully adhering to the ASME Boiler and Pressure Vessel Code, Section VIII. The study further emphasizes the practical implications of utilizing underground storage solutions. In this case, pressure vessels have to endure not only external soil pressure but also temperature fluctuations, thereby ensuring effective storage of hydrogen and adherence to safety guidelines.

ASME Code Reference and Design Considerations

The design of pressure vessels in this study has been referred from the ASME Boiler and Pressure Vessel Code (BPVC), Section VIII [11], which primarily applies to vessels containing water vapour and similar fluids. However, since the fluid is hydrogen gas, additional considerations have been applied due to its high compressibility, low molecular weight, and unique thermodynamic properties at 700–800 bar. The compressibility factor (Z) for hydrogen has been determined using real-gas equations, was integrated into the design process to ensure accurate pressure-volume relationships. While the ASME code provided a baseline for determining the minimum shell thickness using formulas such as $t = (P * R) / (SE - 0.6P)$ for cylindrical shells and $t = (P * R) / (2SE - 0.2P)$ for spherical shells. After FEA simulations, the optimized thickness has been checked against ASME BPVC standards to ensure it remains within permissible limits.

Methodology

This research work focuses on computational analysis using ANSYS to simulate internal pressure effects on each geometry at storage pressures of 700–800 bar. Design parameters were set to maintain equal storage volume across all shapes, ensuring a fair comparison. The analysis was divided into the following steps:

Geometric Modelling

Developed three distinct geometries (sphere, cylinder, and rectangular prism) each configured to store 1 kg of hydrogen under high-pressure conditions (16 litres)as mentioned in the table 1 for spherical, cylinder and table 2 for rectangular prism.

Table 1 Dimension for Spherical and cylinder

Shape	Volume Capacity[litre]	Inner Radius[mm]	Outer Radius[mm]	Inner Height[mm]	Outer Height[mm]	Wall Thickness[mm]
Spherical	16	156	171	-	-	15
Cylinderical	16	60	75	120	270	15

Table 2 Dimension for Rectangular Prism

Shape	Volume Capacity[litre]	Inner Dimension[mm] Length width Height			Inner Dimension[mm] Length width Height			Wall Thickness[mm]
Rectangular Prism	16	200	100	50	230	130	80	15

For each model, these inner dimensions were used for calculating the volume and outer dimensions. The final design has been designed as per BPVC standards.

Finite Element Analysis (FEA): Simulations were conducted in ANSYS to evaluate stress distribution and deformation for each shape, focusing on identifying which structure could withstand pressure without structural deformation.

Following boundary conditions and assumptions are applied

Meshing

A Mesh Independence Study [13,14,15] was carried out to make sure that the Finite Element Analysis (FEA) method to be more accurate and dependable for three type of pressure vessels such as, rectangular, cylindrical, and spherical. This testing procedure has applied different mesh resolutions for the determination of their influence on the analytical indicators deformation, stress, and strain. The idea of the work was to find out which mesh size is the most balanced between reasonable consuming power and result accuracy.

Table 3 Mesh details

	Rectangular Vessel	Cylindrical Vessel	Spherical Vessel
Element Size (mm)	5	5	5
Nodes	3,407	25,304	37,244
Elements	12,363	14,317	141,303

In all cases:
Adaptive Sizing: The medium smoothing and the transition speed to refine the mesh density on the high stress regions were set to the efficient level.
Mesh Defeaturing: It was used to disregard the small geometric elements that were not really important on the analysis and the new mesh contained
Refinement Loops: Two refinement loops were executed within which there was a single loop that had a depth of one, so mesh quality was enhanced in crucial areas.
During convergence, subsequent mesh refinements did not lead to any essential changes in the deformation, stress, and strain values. It proved that the size of partial support was the right one for the inspection that was carried out, and consequently there was still a reliable and efficient calculation of the results. Materials – Stainless Steel, aluminium Alloy and Titanium Alloy (specification as in Default ANSYS software version 2019 R3)
Internal pressure – 700 bar in x,y,z direction
Standard earth gravity – (-Y) direction
Assumption - external surface fully fixed support

Manufacturing Cost Assessment: Manufacturing expenses for each shape, considering material efficiency and complexity of construction were compared

Safety Evaluation: The safety aspects of each design based on likelihood of rupture, material fatigue, and failure modes were evaluated. Safety analysis was particularly critical and focus was given on the high energy release potential of hydrogen under pressure.

Main Study

This section presents a comparative analysis of the three geometries based on simulation data and other assessment criteria.

Structural Durability and Deformation: ANSYS simulations showed that the sphere had the lowest stress concentrations and deformation levels under 700–800 bar, owing to its evenly distributed surface tension. The cylindrical and rectangular prism designs exhibited higher stress concentrations, especially around corners and edges, which made them more susceptible to deformation and potential failure.

Cost Efficiency: Manufacturing analysis indicated that spherical designs, though initially more complex to fabricate, were ultimately more cost-effective due to reduced material usage and enhanced durability, which minimizes the need for frequent replacements or reinforcements.
Safety Considerations: The sphere proved to be the safest shape due to its ability to withstand uniform pressure, making it less prone to rupture. Cylindrical and rectangular designs showed higher potential for structural fatigue, especially under fluctuating pressures common in storage systems.

Results And Discussion
Total deformation, Equivalent stress and Equivalent strain have been analysed for three shapes with three materials in ANSYS software to determine the optimised design and material for usage.

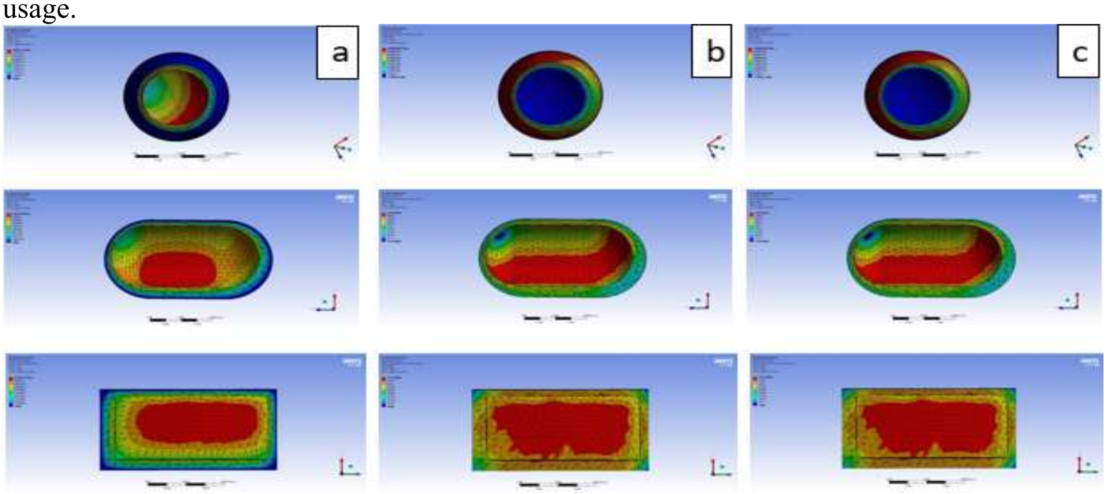

Fig 1 Analysis of Aluminium alloy sphere, cylinder and rectangular (a) Total deformation (b) Equivalent Stress (c) Equivalent Strain

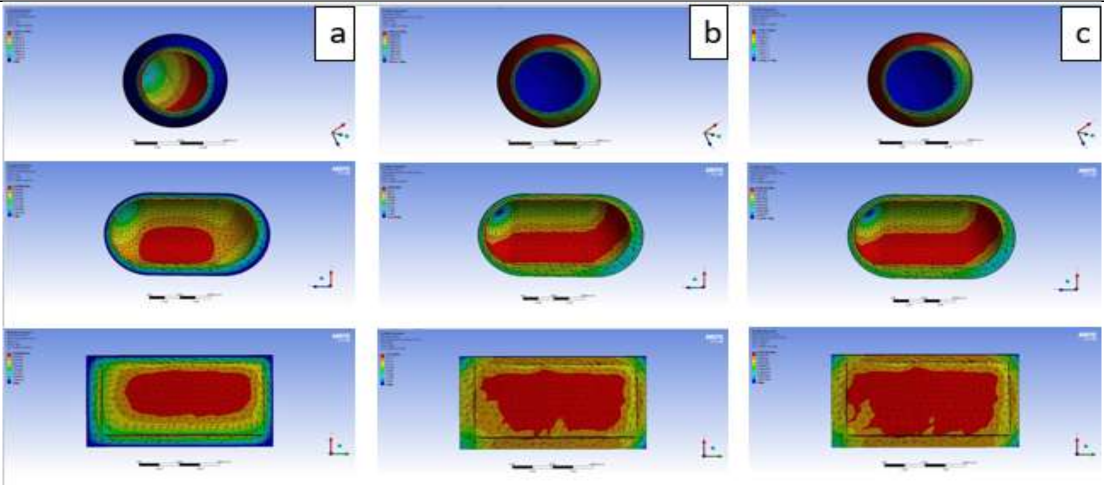

Fig 2 Analysis of Stainless Steel sphere, cylinder and rectangular (a) Total deformation (b) Equivalent Stress (c) Equivalent Strain

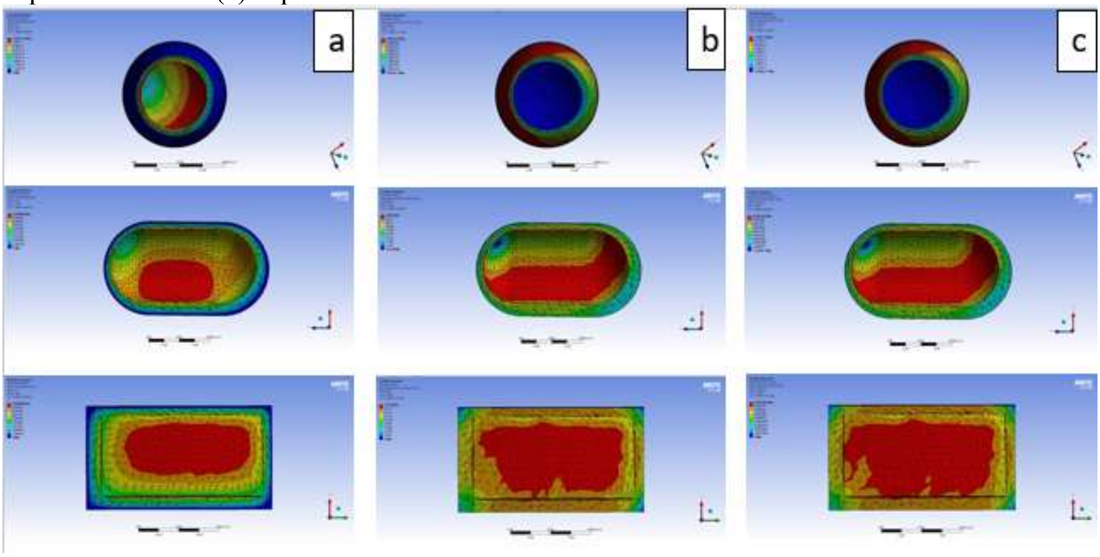

Fig 3 Analysis of titanium sphere, cylinder and rectangular (a) Total deformation (b) Equivalent Stress (c) Equivalent Strain

Even though Stainless steel with spherical containers have deformation ($9.7 x 10^{-8}$mm) and Spherical pressure vessels with aluminium have deformation ($9.81 x 10^{-8}$mm) which are nearly equal. It is optimum to select spherical pressure vessels made of aluminium with minimum equivalent stress of $6.09 x 10^{-4}$ MPa and minimum equivalent strain $8.58 x 10^{-9}$ MPa. After FEA simulations, the optimized thickness has been checked against ASME BPVC standards to ensure permissible safety limits

CONCLUSION

The results confirm the superiority of the spherical pressure vessel in all structural performance metrics. The spherical stainless-steel container exhibited a deformation of 9.7×10^{-8} mm, while the spherical aluminium alloy container showed a deformation of 9.81×10^{-8} mm, indicating nearly identical structural responses. However, the aluminium alloy vessel demonstrated minimum equivalent stress of 6.09×10^{-4} MPa and an equivalent strain of 8.58×10^{-9}, making it the optimal choice due to its lower stress concentration and improved safety margins.

While stainless steel offers slightly lower deformation, its manufacturing cost is 17% higher than aluminium based on Indian standards. The even pressure distribution of the sphere minimizes the risk of structural failure, reinforcing its suitability for underground hydrogen storage. After conducting FEA simulations, the optimized wall thickness was verified against ASME BPVC standards, ensuring compliance with permissible safety limits.

This study validates the industrial feasibility of aluminium spherical tanks as a viable and efficient solution for high-pressure green hydrogen storage applications.

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